

A Conceptual Study for the Autonomous Direct Forming of Lunar Regolith into Flexlock™ Geomats for Lunar Surface Operations

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Herein we describe the conceptual method of an autonomously operable Direct Forming machine that would consume regolith or regolith slag to mold intimately, interlinked elements in a continuous process. The resulting product, one to three meter wide geomats, would be deployed over commonly traversed areas to isolate the astronauts and equipment from underlying dust. The porous geotextile would provide areas for dust settling, thereby mitigating dust impingement on astronaut suits or surface structures. Because of their self-supporting yet flexible structure, these geomats could be assembled into shields and buttresses to protect lunar habitants from radiation, forming a "flexoskeleton" from *in situ* materials.

I. Introduction

In the NASA 2004 Vision for Space Exploration, President Bush outlined a strategic goal to put a sustained human presence on the moon by 2020.¹ To make a sustained presence possible several key technologies must be developed that address concerns raised by astronauts during the Apollo lunar landings. During lunar surface excursions, astronauts were exposed to significant amounts of lunar regolith dust. The abrasive dust was found to bind to surfaces via electrostatic forces thereby contaminating machines, space suits, and optics.² The dust problem was a major concern for the astronauts during extra-vehicular activity (EVA) space walks and rover activities. The long-term affects of regolith on potential lunar dwellings is currently unknown, but likely to be problematic where optical systems, vacuum seals, mechanical joints, and electrical functionality will be adversely affected. For a sustainable presence on the moon, a dust mitigation system will be required for commonly traversed areas.

Lunar outpost and settlement scenarios have layouts that would require repeated traveling, by foot or by rover, between permanent structures such as habitations, processing and storage facilities, and landing and launch areas.³ Similar to earth, the lunar roads or walkways would reduce the formation of dust contamination. However, the means to construct these pathways has not been down-selected due to pending equipment requirements for ISRU excavation and astronaut transportation vehicles. As resource requirements are being validated to support function versus weight-to-orbit concerns, several means to site preparation are being researched within and outside of NASA. The logical approach to creating roads on the moon is excavation. Paving these roads with lunar concrete,⁴ regolith sintering,⁵ and other technologies have been proposed to take advantage of the fine, loose, easily compressible particulate regolith covering the top 1-2 centimeters of the lunar surface.

The density of the regolith increases with depth. The best estimates for bulk density of soil are about 1.5 ± 5 g/cm³ between 0 and 15 cm depth, 1.58 ± 5 g/cm³ between 15 and 30 cm and 1.74 ± 5 g/cm³ between 30 and 60 cm depths.⁶ Excavation using a lunar bulldozer or ISRU soil extraction machine would remove the soft top soil layer; leaving the harder, more densely packed regolith underneath. However, loose soil neighboring the cleared area would still be tracked onto the cleared area thus recreating the problem albeit at a lesser scale. In addition, foot and rover traffic might over time loosen the densely packed regolith that was exposed during excavation. The weight-to-orbit concerns for an excavation unit are significant; therefore, modifications to existing equipment, such as the

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NASA Chariot and ATHLETE are being conducted. These modifications, such as a blade on the end of Chariot or excavation tool attachment to ATHLETE, would provide versatility to the existing vehicle but would not address the reoccurring dust buildup from neighboring areas.⁷ These technologies require further evaluation of power usage, mass to orbit, and speed of site preparation if they are to be implemented in a lunar habitat.

Amalgam Industries and NASA's Kennedy Space Center's Applied Technology Directorate are collaborating to develop a novel geotextile for dust mitigation and lunar surface stabilization. This geotextile can be made on the lunar surface using lunar regolith or regolith slag from any of a number of *in situ* resource utilization (ISRU) oxygen extraction processes.⁶ The resulting metal-ceramic geotextile would be flexible and conformable to the cratered, uneven lunar surface terrain. The porosity of the Flexlock structure would provide a pathway for dust settling that would inhibit further dust contamination. Herein we describe the conceptual method for manufacturing and implementation of ceramic-based Flexlock materials for use terrestrially or on the moon.

II. Flexlock Technology

Direct Forming is an automated process for making flexible lamina by sequentially and continuously forming or forging rigid, interconnected elements.⁸ Originally conceived as a new terrestrial process to convert polymer feedstocks to high value flexible sheet components for consumer luggage products, the versatility and efficiencies inherent in this material conversion concept may help solve the lunar geotechnical challenges discussed above.

In Direct Forming, relatively simple clamshell mold halves are arrayed on two matching surfaces. A moldable or forgeable feedstock metered into the cavities between these clamshell molds form a continuous array of substantially identical elements. These elements have protruding hinge connecting portions extending along each of their sides. These first formed elements, called "male" elements, are shaped such that the hinging axes of these connecting portions intersect along the sides of a right isosceles triangle, like those shown in white in Figure 1. Then, a second type of clamshell mold, called the composite mold, holds the arrayed male elements in position while the second type of elements, "female elements", are similarly molded in sequential order between and among the arrayed male elements. This second type of clamshell mold both holds the previously molded male elements in position as well as incorporates their connecting portions into the molding surfaces for forming the females elements, so that the female elements are molded directly over and thus hinged onto the adjacent male elements.

A photograph (Figure 1, right) is an example of a flexible polymer sheet of these intimately formed and simultaneously linked rigid elements.

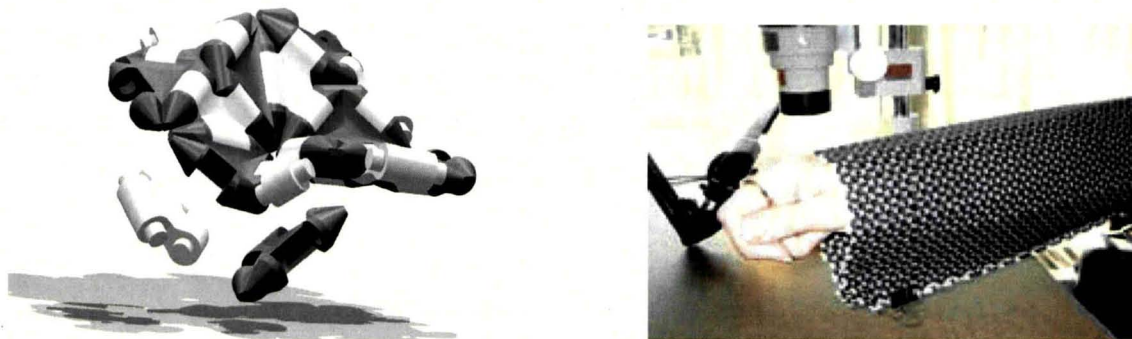


Figure 1. Flexlock lamina portion with a white "male element" and gray "female element" (left). Prototype polymer Flexlock sheet (right).

The schematic form of the underlying principle behind the Direct Forming process is shown in Figure 2. For simplicity, only three adjacent male elements (in red) are shown in the array. In the upper left, three molded male components are moved into the composite clamshell mold. Next, a forgeable material is fed into the composite mold (lower left). The female element is formed in place (as shown in the upper right)– directly formed – against the connection portions of the male elements. At the lower right a finished male-female subassembly is shown.

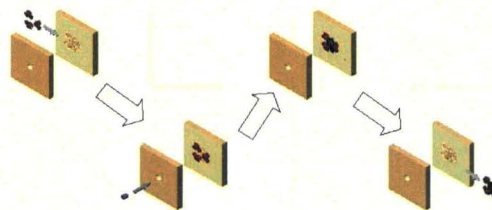


Figure 2. Principle schematic of the Direct Forming Process.

The Direct Forming machine (Figure 3) demonstrates where the various types of clamshell mold surfaces come together at the "nips" of a series of rollers. The rollers have arrayed dimples which constitute half of each clamshell mold for each male or female element. Arrayed around each molding roller are various processing stations that place and condition the feedstock used for molding. In this case pelletized or powdered polymers are used for demonstrative purposes. The enlarged image on the left of Figure 3 shows the array of dark male elements which, in this example, have a more complex multiple knuckle and continuous pintle hinge portion. This shape can be made by simple clamshell molds formed at the nip between roller 1 and roller 2. As shown, the arrayed male elements are transferred to the composite mold on the second set of rollers, still in their arrayed positions, from the first set of rollers. Moldable feedstock is then distributed to the open portions of the composite mold and this material is molded at the nip between rollers 3 and 4 where it is formed into the arrayed female elements and simultaneously linked with the male elements, resulting in the finished lamina shown at the right portion of Figure 3. As proposed here, lunar regolith or regolith slag would be the supply rather than thermoplastic polymers.

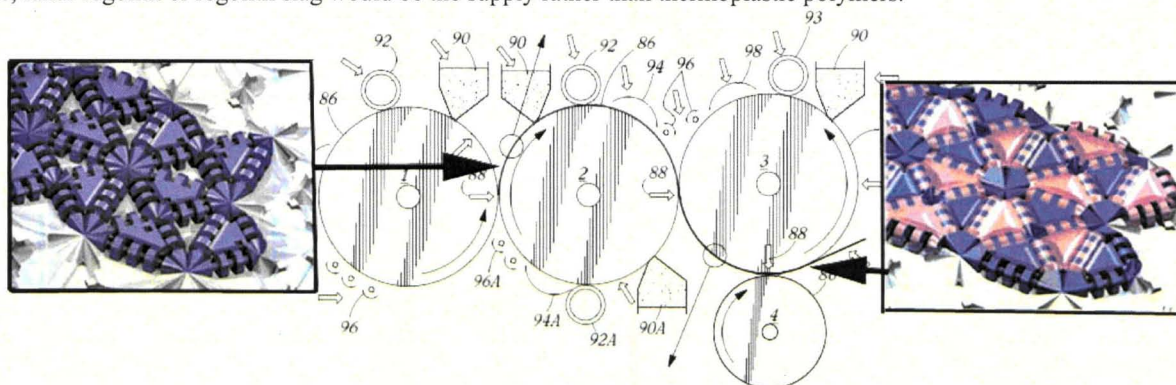


Figure 3. Direct Forming machine with male elements arrayed on mold surfaces (left), roller alignment (center), and resulting lamina (right).

Flexlock and Direct Forming represent a shift from the current incremental improvements in paving by applying modern materials science and novel mechanical engineering production techniques to the ancient concept of interlocking blocks, such as the hand assembled paving shown in Figure 4. In contrast, an autonomously produced Flexlock geomat, as illustrated in prior patent drawings,⁸ would have a robust interlinked design that possesses up to four bending axes, thus providing adequate flexibility to conform to the underlying soil. Gaps and spaces between interlocked brick-sized elements would provide controlled porosity to capture regolith dust.

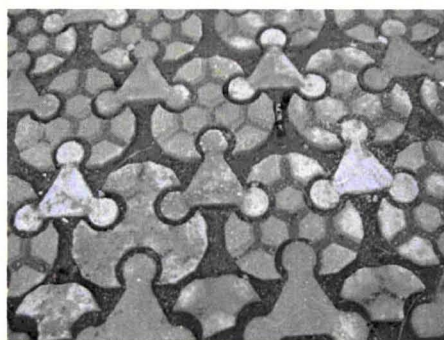


Figure 4. Hand laid interlocking pavers.

In-place production is inherent to the Direct Forming business model. For terrestrial consumer markets, a relatively low value versatile high performance-to-weight feedstock (conventional or engineered thermoplastics, aluminum, titanium and magnesium) are converted to non-textile fabrics for use in luggage, footwear, commercial seating, etc. Direct Forming has the capability of being produced at the retail establishment and on demand. When fully realized, this in-place manufacture would be embodied in a Direct Forming machine that is not much larger, nor more complex, than a large computer printer. Similarly, a Direct Forming machine could be developed to make geotextiles on the moon.

Terrestrially, Direct Forming uses a minimum amount of energy to convert moldable feedstocks directly into non-textile lamina. Thus, the rate of energy usage would be relatively small in comparison to those processes used to make lamina, components or materials that Flexlock will displace, for example, injection molding, vacuum forming and other energy intensive conversion processes. On the lunar surface, energy requirements will be driven by other higher demand systems such as the ISRU oxygen production system.

III. Conceptual Design of Flexlock Geomats

Our conceptual design can be implemented as either an autonomous Direct Forming machine that converts regolith into Flexlock geomats or in sequence to the ISRU oxygen production plant to produce Flexlock geomats from processed *in situ* regolith slag. Both methods would involve collecting the regolith dust and consolidating the regolith to form Flexlock elements, Direct Forming these elements into continuous sheets of Flexlock non-textile fabric, and placing the thus-formed structural but flexible regolith mats on the regolith deposits to make paths, roadways, landing strips, blast shields, etc. These geomats would be layered over and thus isolate the unconsolidated regolith deposits from being disturbed by rocket blasts and other lunar activities.

Harvesting regolith would be accomplished using robotic excavation machinery currently being developed and will not be further discussed here.⁷ Once the regolith is harvested, the material would be processed to remove oxygen for human consumption or fuel propellant. Oxygen production from regolith can be accomplished using several methods; however, all methods require heating the regolith to very high temperatures. The resulting slag, which would still have varying amounts of oxides in the form of metal oxides and silicates, would then be used as a feedstock to fill the Direct Forming clamshell molds. Due to the brittleness of the glass-ceramics formed during this process, a small amount of a binder may first be mixed with regolith to form the basic feedstock. The feedstock, with or without binder, would then be further heated and metered into the forming plates and compressed to form male and female Flexlock element performs (Figure 1). One sintering system would use a very small amount of a powdered metal such as lithium or potassium to form an oxide flux that would solid phase sinter at least the feldspar or silicon dioxide constituents of the regolith powder by heating and pressure forming of the regolith perform. This feedstock would have a relatively low sintering temperature, since the sodium oxide would act as a flux to bind the regolith particles together. A possible second approach would be to use a small amount of an organic binder which would crosslink via ultraviolet light after deployment. Waste products, especially polymers used in food storage, could be used as binders. This approach would be highly dependent of the binder concentration due to cost-to-orbit constraints. The molding, forging and compression of regolith and regolith-binder analogs are being explored.

Unprocessed lunar regolith could be used as a feedstock for the direct forming process. The fine powdered regolith could be put into the molds and then heated until it sintered to form the geomat. Alternatively, the regolith could be heated to melting or brought to a temperature near melting and injected into the mold. Either of these methods would allow the geomat to be made independently of any other ISRU applications, but would require a heat source to bring the regolith to the appropriate temperatures (1000 – 1200°C). This would allow flexlock to be made and used for surface stabilization before other infrastructure is brought into place. If built in a modular fashion, the heat source could be taken from the direct forming apparatus and shifted to ISRU applications as needed. The temperatures needed for sintering the regolith can be achieved with a solar concentrator, microwave or conventional heating methods.

Similar to chain mail, the resulting Flexlock geomat made of sintered or bound regolith would have striking physical characteristics, especially in view of the relatively low amount of Earth-based material needed to create these geomats. The Flexlock geomat would be remarkably resistant to solar radiation, flexible, and possess adequate compression and tensile strength required for human and vehicular traffic. The inherent structural, self supporting and erecting characteristics of Flexlock, that is, its ability to be formed into self-supporting structures, would also facilitate wrapping vertical structures with Flexlock geomats to further insulate regolith plumbing not suppressed by the horizontally layered geomats.

Deployment of the Flexlock geomats could be performed robotically or by a team of 2 astronauts. On Earth, civil engineers use geosynthetics (e.g. geomats and geogrids), ballast or riprap, paving and shoring. These materials are used alone or in various layers or combinations to help with terrestrial geotechnical issues such as roadway and bank

stabilization and construction, erosion control, and dust and silt control. An autonomously operating Direct Forming apparatus, whether it uses rollers as above, or shuttling plate or belt mounted clamshell molds, would consume regolith or slag to mold intimately interlinked male and female elements in a continuous process. After forming, these geomats would be flexible enough to roll into large cylindrical bundles for later placement or could be laid down directly onto prepared or semi-prepared lunar surfaces as they exit the Direct Forming machinery. The resulting geomats would combine the functions of geomembrane, geogrid, ballast, and paving when deployed over commonly trafficked paths and layered over vehicle landing areas. Their tensile strength should be adequate to maintain physical integrity during handling and placement under lunar gravity. These selectively porous Flexlock geocomposites would provide areas for dust settling, thereby mitigating dust impingement on astronaut suits or surface structures.

It is possible to deploy the geomats in a shingling or layered assembly. For example, in order to prepare a landing site for the arrival of a lunar vehicle, Flexlock geomats would be deployed in a large rectangular area, starting at the perimeter and moving towards the center by overlapping up to half the width of each geomat strip with a subsequent Flexlock layer. This would result in a self-sealing, shingled structure that would be thickest at the center of the landing area, tapering out to at least one and perhaps two geomat layers towards the perimeter. This multiple layered thickness in the center would resist repeated down blasts and repeated physical abuse, isolating any of the inevitable breaking or cracking of the Flexlock elements via this multiple layering. The Flexlock geomats would be ideal for covering paths or roadways leading away from the landing site towards other permanent facilities. As mentioned above, Flexlock geomats will have the structural and physical characteristics to shelter other structures close to the proposed landing area. Shields or buttresses made from Flexlock geomats would be wrapped around the structures to mitigate regolith plume and perhaps be a sacrificial micrometeorite shield. Regolith geomats could serve as shoring for berms, burying of reactors and dwellings, or to form buttresses to protect lunar habitants from radiation.

To date, Direct Forming and Flexlock materials have only been used with conventional thermoplastic resins and injection molding to distribute the moldable material to the clamshell mold to Direct Form the elements against one another. Thus, considerable development needs to be done, not only to scale up Direct Forming machinery and processes, but also to test, evaluate and confirm that this method can be extended to metals and ceramics. Feasibility experiments are underway to examine how unconsolidated regolith or regolith slag can be used as the bulk material for the directly formed Flexlock elements. The difficulty lies in how the chosen type of regolith can be molded in a way that it would hold and maintain the element shape under stress while providing optimum compression and tensile strength. Trade studies are being initiated for the cost to benefit analysis for an autonomous, continual operation of a dependable Direct Forming machine that can produce adequate geomats for automated placement or hand placement in anticipation of subsequent manned visits. Proper thermal melt/cooling cycles are being examined to minimize friction or bonding between adjacent male and female regolith elements to prevent brittle fracture points and form the necessary mechanical joint.

The development of this technology could be adapted to process more sophisticated terrestrial feedstocks to produce more robust structures. Terrestrial applications such as geomats for construction, portable foundations, and platforms for unstable ground structures provide incentive for developing versatile element geometry. Several element geometries will be examined to ascertain optimum structure-property relationships.

IV. Summary

The technical challenges to construct *in situ* regolith geomats are significant but not insurmountable. The major advantage of this scenario would be reducing the tremendous energy and EVA burden required to perform civil engineering to construct roadways and pathways on the moon. The feedstocks necessary to form these geomats are readily available from *in situ* regolith oxygen production, and minimal tooling will be required to modify the oxygen production plant to produce the geomats. Once produced, the rolled geomats can be easily moved and deployed using ATHLETE or by an astronaut. Based on a materials approach, the regolith geomats would be able to withstand lunar diurnal thermal cycling, radiation, and other physical stresses of lunar transport and habitation, while providing structural support with minimal energy, maintenance, or equipment. Terrestrial applications will be explored to generate relative environmental testing and feasibility deployment for *in situ* production capabilities.

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